Terahertz Sensing for Fruit Spoilage Monitoring

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***Abstract*—A novel method was presented in this paper to obtain the absorption coefficient of pear and apple slices based on the scattering parameters, which were measured by employing Vector Network Analyzer (VNA) extended into the Terahertz (THz) frequency range of 0.75 THz to 1.1 THz with Swissto 12 waveguide systems. The results show the significant difference of absorption coefficient and transmission response between pear and apple slices when the Moisture Content (MC) value is less than 50% with the passing days. The comparison results display that the decreasing ratio of the absorption with the MC in apple slice is nearly three times faster than that in pear slice due to the different characteristics of the internal constituents and texture structures in the THz region. The application presented in this paper can be applied to detect the chemical characteristics and the signatures of inner compositions for quality control in fruits.**

***Index Terms*—terahertz wave, fruits, absorption coefficient, scattering parameter, moisture content**

I. Introduction

The Terahertz (THz) radiation, which is the non-ionizing Electromagnetic (EM) waves in the range of 0.1 THz to 10 THz with the lower photon energies than 4 meV/1 THz [1], is being widely studied and developed become of promising application including spectroscopy and communication [2], sensing and imaging [3], preventive health care, and non-destructive evaluation [4]. Due to the safety of THz radiation to tissues and biomolecules of food and any live cells, the THz technique has become a novel and powerful non-destructive technologies to be explored for monitoring the quality of food and recognizing the inner intermolecular characteristics of biological materials in the THz range [5]. The melamine in food products was identified and classified with the obvious absorption characteristics in the THz region [6]. The antibiotic and harmful pesticide in food could be detected because of the intrinsic resonance properties of chemicals and biomolecules in the THz radiation region [7] [8]. The potential applications of the THz technology in agricultural food industry have been comprehensively summarized in [9] [10]. Unlike some existing Nuclear Magnetic Resonance (NMR) and Near-Infrared (NIR) techniques [11] [12], the THz technology can be able to obtain more detailed internal characteristics of fruits due to its high resolution and sensitivity at molecular vibration. Meanwhile, the THz sensing can be employed to detect the refractive index, absorption coefficient and the dielectric properties of the samples [10]. It has been proved that the dielectric properties of fruits and vegetables have some connection with MC or water activity [13] [14], which is the main factor that causes the changes of electrical characteristics because of the different inner substances present in fruits and vegetables [15]. Consequently, the quality of fruit is mainly dominated by the MC value. In [16], the relationship between X-ray absorption and the physicochemical quality parameters in mango were presented.

As the abundant information regarding the internal chemical and physical properties of tissues obtained by employing the THz waves, recently, the non-destructive techniques of the spectroscopic method are becoming an increasing interest in the evaluation of quality attributes and security for fruits [17]. The absorption coefficient of the sample to the electromagnetic waves indicates the interacts of waves and biological tissue, and this can be applied to characterize the constituents in the fruits including MC and Soluble Solids Content (SSC). In [18], quantification of the SSC in apples was determined by utilizing terahertz Time-Domain Transmission Spectroscopy (THz-TDTS) technology. In [19], the SSC was quantitatively predicted by investigating NIR spectroscopic techniques. Moreover, due to the different absorption properties of the chemical and biological tissue in the THz frequency range, chemical residual detection was studied by using the THz Time-Domain Spectroscopy (TDS) technique [20].

The paper is aimed to provide a simple method of employing THz technology to monitor the variations of the MC value of apple and pear slices and derive the absorption coefficient by employing the transmission response from measurements of the VNA with the Swissto12 system in the THz frequency range of 0.75 THz to 1.1 THz. These preliminary results provided significant information to study the more detailed characteristics of substances existing the inner fruits through the more dielectric properties including permittivity, permeability and refractive index in the THz frequency region.

The paper is arranged as follows: Section II presents the experimental samples and measuring methods. Section III shows the analysis and discussion of the experimental results. Finally, the conclusion is presented in section IV.

II. Materials and Experimental Methods

A. Samples

The apple and pear slices with the thickness in the range from 40μm to 4mm and the similar size were taken as experimental samples to be measured under the environmental temperature of 15°C ± 0.2°C and humidity of 30% ±2%. To obtain the average measurements, each slice was taken at four different locations, and each location was measured four orientation with three readings each time for consecutive days until the sample slices were dried out fully. Moreover, the weight of each slice was collected before taking the measurement employing a digital scale with an accuracy of 0.1 mg to be used to calculate the moisture content value.

B. Experimental Setup

The experimental setup consists of three parts, VNA, the Material Characterization Kit (MCK) Swissto 12 waveguide system, and two waveguide extender ports in the frequency range from 0.75 THz to 1.1 THz [21], as shown in Fig. 1. Prior to taking any measurements, an appropriate calibration is required with two-port Short-Open-Load-Thru (SOLT) criterion to diminish the losses existed in the system and the errors occurred whilst taking measurements [22]. Subsequently, the scattering parameters (S-parameter) of samples including the transmission (S12, S21) and reflection (S11, S22) responses can be determined based on VNA in the frequency range of 0.75 THz to 1.1 THz.

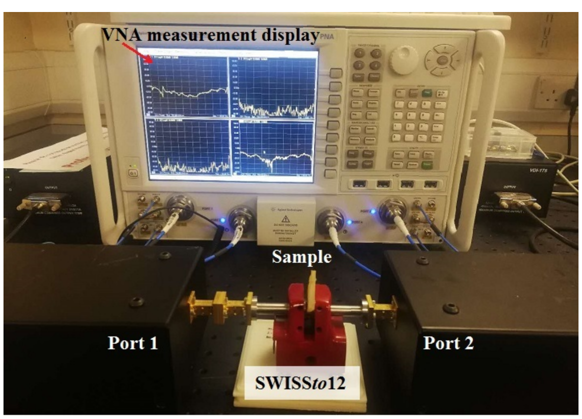


Fig. 1: Experimental setup of THz system for measuring the transmission response with Swissto 12.

C. Analysis Methods

The weight of each fruit slice was converted into MC value with the passing time according to (1).

$$Value_{MC} = \frac{W_{sample} - W_{dry}}{W_{sample}} \times 100\% \tag{1}$$

Where $Value_{MC}$, the MC value. W_{sample} indicates the weight of slice at the measuring time. W_{dry} denotes the weight of the slice dried out completely.

To calculate the absorption coefficient of the sample, $\alpha_s(\omega)$, the reflection coefficient, $r_s(\omega)$, and transmission coefficient, $t_s(\omega)$, were obtained from the measured S-parameters respectively as follows [23].

$$r_s(\omega) = \mathrm{X} \pm \sqrt{X^2 - 1} \tag{2}$$

$$t_s(\omega) = \frac{S_{11} + S_{21} - r_s(\omega)}{1 - (S_{11} + S_{21})r_s(\omega)} \tag{3}$$

Here, the reflection coefficient should comply with $|r_s(\omega)| \le 1$ for passive samples. ω is the angular frequency of the THz waves. And the middle parameter, X, can be derived from (4).

$$X = \frac{1 + (S_{11} - S_{21})(S_{11} + S_{21})}{2S_{11}} \tag{4}$$

Moreover, with $t_s(\omega) = \exp\{j\omega d n_s(\omega)\}$, the complex refractive index, $n_s(\omega)$, can be obtained. d is the thickness of the sample. Finally, the absorption coefficient, $\alpha_s(\omega)$, can be extracted from (5) [24].

$$\alpha_s(\omega) = \frac{2\omega \cdot Imag\{n_s(\omega)\}}{c} \tag{5}$$

Where $Imag\{\cdot\}$ indicates the imaginary part. c is the velocity of light.

III. Results and Discussion

In this section, the correlation of absorption coefficient with the transmission response of apple and pear slices was discussed. Moreover, the correlation of absorption coefficient against MC value was presented with the passing days. The decaying pattern of the apple and pear slices with the value of moisture content was as shown in Fig. 2.

A. Correlation of Absorption Coefficient with the Transmission Response

The transmission response obtained directly from VNA appears the attenuation caused by the absorption of fruit slices to the electromagnetic in the THz region. Here, the absorption coefficient and the transmission response of apple and pear slices against the THz frequency were as shown in Fig. 3(a) and Fig. 3(b). The top half of the figure shows the absorption coefficient corresponding to the left y-axis with the unit of cm-1, and the bottom represents the transmission response corresponding to the right y-axis with the unit of dB. The samples showed a clear increasing trend of the absorption

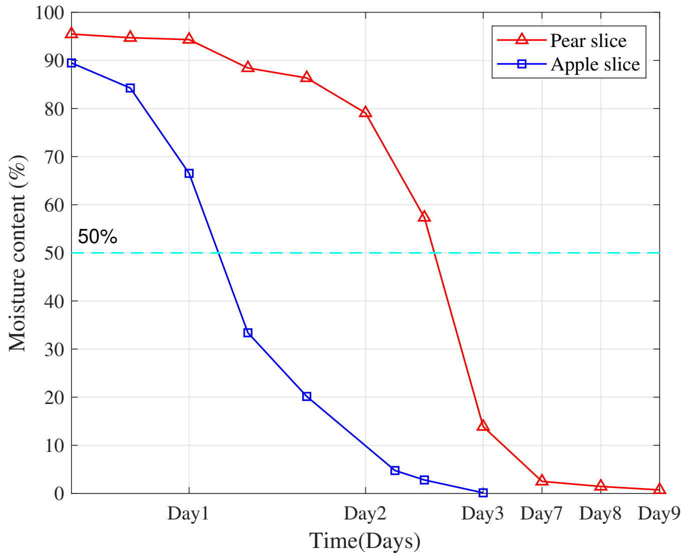


Fig. 2: MC values of samples with days.

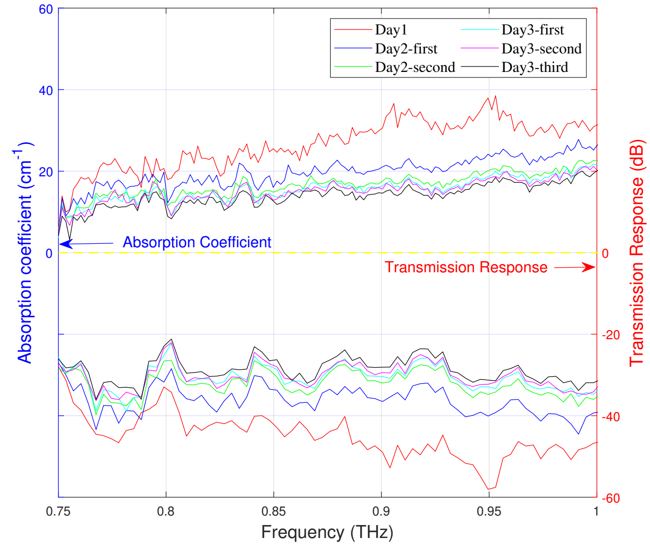
characteristic with the frequency in the range of 0.75 THz to 1.0 THz, nevertheless, the transmission response of the samples was decreased with the frequency. Compared Fig. 3(a) with (b), it illustrated obviously that the relationship between the absorption coefficient and transmission response was very clear when the MC value was lower than 50% referred to Fig. 2.

Due to the different texture and inner substances of pear and apple, especially the loss rate of the water with the passing days, the apple slice showed the significant difference in absorption characteristic and transmission response on day 1 to day 3. Nevertheless, the pear slice illustrated a distinct variation in the absorption coefficient and transmission response until the MC value was declined to lower than 50% from day 3 to day 8.

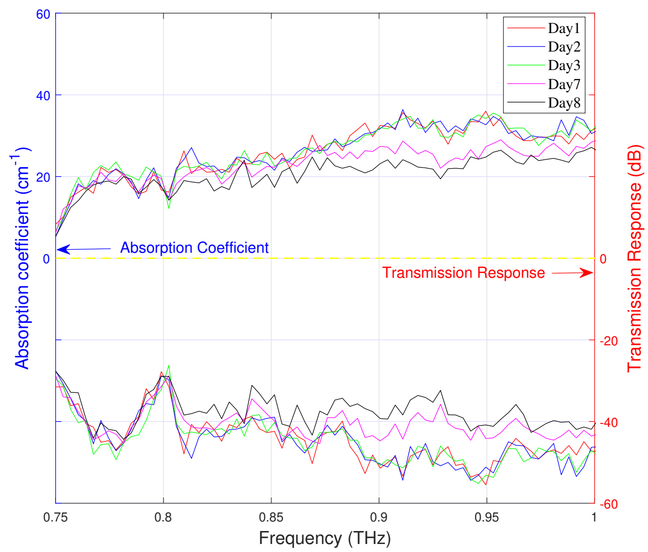
In Fig. 3(a) and (b), the strong absorption peak can be observed clearly when the MC value is larger than 50% due to the more water in the samples. That indicates that the absorption of the water to the THz radiation played a decisive role in this case. With the passing days, the loss of the water was more and more, and the difference of the absorption characteristic of the apple and pear slices was more distinguished in the THz region, which can be employed to determine the presence of pesticides or more intermolecular information of fruits and further realize the quality and security control.

B. Correlation of Absorption Coefficient with MC

For the investigated slices of this paper, the relationship between the absorption coefficients against the MC value at the frequency of 0.95 THz was as shown in Fig. 4. It depicts the absorption of different slices as a function of the moisture content with the passing days, which also implies that the influence of the variation of the concentration of inner constituents in the fruits is very less in the case of neglecting



(a) Absorption coefficient with transmission response of Apple slice



(b) Absorption coefficient with transmission response of pear slice

Fig. 3: (a) and (b) shows the relation of absorption coefficient with transmission response from 0.75TH to 1.0 THz with days.

the scattering losses [25]. Observed the trends of the curves, the blue fitting for pear slice and the red fitting for apple slice, as shown in Fig. 4, the percentage of the reduced absorption from day 1 to day 3 was around 57% for the apple slice, while, it was only about 28.6% from day 1 to day 8 for the pear slice. Due to the dominant position of moisture content, the related dielectric properties including the permittivity, permeability of samples can be further estimated to determine the chemical composition and texture structure of the different fruits for non-destructive quality control in the future research.

IV. Conclusion

This paper was mainly aimed to highlight the moisture content, the transmission response and absorption coefficient of pear and apple slices by employing the transmission response

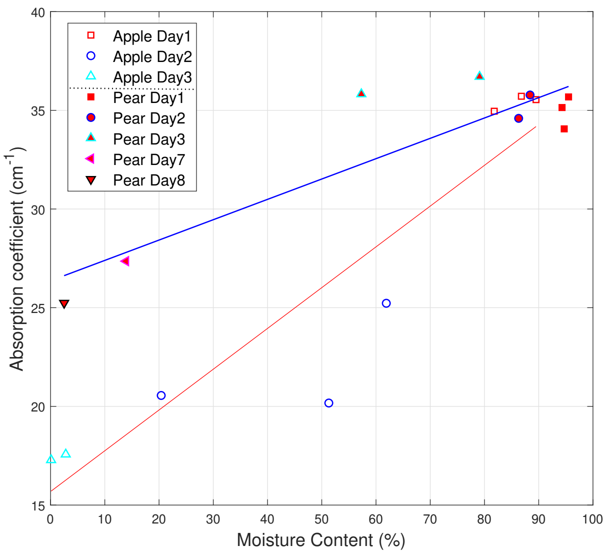


Fig. 4: Absorption coefficient against MC of slices with days.

derived from VNA measurements with Swissto 12 waveguide system in the THz region from 0.75 THz to 1.1 THz. The novel technique for detecting the absorption coefficient and measuring the MC of fruits using THz sensing technology has significant advantages to determinate the concentrations of inner ingredients in fruits including soluble content, carbohydrates and other minerals. In this paper, the proposed method can be used to determine the absorption coefficient and the percentage of MC in fruits with the passing days, moreover, the electrical properties and chemical characteristics of inner tissue can be derived from S-parameter of the samples based on the novel algorithm such as machine learning and pattern recognition.

References

[1] K. Wang, D. W. Sun, and H. Pu, "Emerging Non-Destructive Terahertz Spectroscopic Imaging Technique: Principle and Applications in the Agri-food Industry," Trends in Food Science & Technology, Vol. 67, pp. 93–105, September 2017.

[2] J. Federici, and L. Moeller, "Review of Terahertz and Subterahertz Wireless Communications," Journal of Applied Physics, Vol. 107, pp. 111101, June 2010.

[3] J. F. Federici, "Review of Moisture and Liquid Detection and Mapping Using Terahertz Imaging," Journal of Infrared, Millimeter and Terahertz Waves, Vol. 33(2), pp. 97-–126, Feb 2012.

[4] A. F. Ren, A. Zahid, D. Fan, X. D. Yang, M. A. Imran, A. Alomainy, and Q. H. Abbasi, "State-of-the-Art in Terahertz Sensing for Food and Water Security – A Comprehensive Review," Trends in Food Science & Technology, Vol 85, pp. 241-251, March 2019.

[5] Á. Kertész, Z. Hlaváćová, E. Vozáry, and L. Staroňová, "Relationship Between Moisture Content and Electrical Impedance of Carrot Slices During Drying," *Int. Agrophysics*, Vol. 29(1), pp.61–66, Jan 2015.

[6] S. H. Baek, H. B. Lim, and H. S. Chun, "Detection of Melamine in Foods Using Terahertz Time-Domain Spectroscopy," Journal of Agricultural and Food Chemistry, Vol. 62(24), pp. 5403-–5407, June 2014.

[7] A. Redo-Sanchez, G. Salvatella, R. Galceran, E. Roldós, J. A. García-Reguero, M. Castellari, et al. "Assessment of Terahertz Spectroscopy to Detect Antibiotic Residues in Food and Feed Matrices," Analyst, Vol. 136(8), pp. 1733-–1738, Feb 2011.

[8] Y. Hua, and H. Zhang, "Qualitative and Quantitative Detection of Pesticides with Terahertz Time-Domain Spectroscopy," IEEE Transactions on Microwave Theory and Techniques, Vol. 58(7 PART 2), pp. 2064-–2070, July 2010.

[9] K. Wang, D. W. Sun, and H. Pu, "Emerging Non-destructive Terahertz Spectroscopic Imaging Technique: Principle and Applications in the Agri-food Industry," Trends in Food Science & Technology, Vol. 67, pp. 93-–105, September 2017.

[10] A. A. Gowen, C. O'Sullivan, and C. P. O'Donnell, "Terahertz Time Domain Spectroscopy and Imaging: Emerging Techniques for Food Process Monitoring and Quality Control," Trends in Food Science & Technology, Vol. 25(1), pp. 40–46, May 2012.

[11] A. D. C. Santos, F. A. Fonseca, L. M. Liao, G. B. Alcantara, A. Barison, "High-resolution Magic Angle Spinning Nuclear Magnetic Resonance in Foodstuff Analysis," TrAC Trends in Analytical Chemistry, Vol. 73, pp. 10-–18, Nov 2015.

[12] R. Beghi, G. Giovanelli, C. Malegori, V. Giovenzana, R. Guidetti, "Testing of a VIS-NIR System for the Monitoring of Long-term Apple Storage," Food and Bioprocess Technology, Vol. 7(7), pp. 2134-–2143, July 2014.

[13] O. Sipahioglu, S.A. Barringer, "Dielectric Properties of Vegetables and Fruits as a Function of Temperature, Ash, and Moisture Content," Food Science, Vol. 68(1), pp. 234–239, Jan 2003.

[14] Y. Q. Zhao, S. Men, J. X. Liu, J. Wu, and L. Yan, "Review: Application of Non-destructive Techniques for Fruit Quality Classification," Advance Journal of Food Science and Technology, Vol 12(7), pp. 388–395, Nov 2016.

[15] D. Khaled, N. Novas, J. Gazquez, R. Garcia, and F. Manzano-Agugliaro, "Fruit and Vegetable Quality Assessment via Dielectric Sensing," Sensors, Vol. 15(7), pp.15363-15397, June 2015.

[16] E. G. Barcelon, S. Tojo, K. Watanabe, "Relating X-ray Absorption and Some Quality Characteristics of Mango Fruit (Mangifera Indica L.)," Journal of agricultural and food chemistry, Vol. 47(9), pp. 3822-3825, Aug 1999.

[17] D. Hu, X. P. Fu, A. Ch. Wang, Y. B. Ying, "Measurement Methods for Optical Absorption and Scattering Properties of Fruits and Vegetables," Transactions of the ASABE (American Society of Agricultural and Biological Engineers), Vol. 58(5), pp. 1387-1401, June 2015.

[18] G. H. Hao, J. J. Liu, Z. Hong, "Determination of Soluble Solids Content in Apple Products by Terahertz Time-Domain Spectroscopy", Proc. SPIE 8195, International Symposium on Photoelectronic Detection and Imaging 2011: Terahertz Wave Technologies and Applications, 819510, Aug 2011.

[19] J. Li, W. Huang, C. Zhao, B. Zhang, "A Comparative Study for the Quantitative Determination of Soluble Solids Content, pH and Firmness of Pears by Vis/NIR Spectroscopy," Journal of Food Engineering, Vol. 116(2), pp. 324–332, May 2013.

[20] Y. Hua, and H. Zhang, "Qualitative and Quantitative Detection of Pesticides with Terahertz Time-Domain Spectroscopy," IEEE Transactions on Microwave Theory and Techniques, Vol. 58(7), pp. 2064–2070, July 2010.

[21] A. Khalid, D. Cumming, R. Clarke, C. Li, and N. Ridler, "Evaluation of a VNA-based Material Characterization Kit at Frequencies from 0.75 THz to 1.1 THz," In Proceedings of IEEE 9th UK-Europe-China Workshop on Millimetre Waves and Terahertz Technologies, Sept 2016.

[22] A. Zahid, K. Yang, H. Heidari, C. Li, M. A. Imran, A. Alomainy, and Q. H. Abbasi, "Terahertz Characterisation of Living Plant Leaves for Quality of Life Assessment Applications," in URSI 2018 - Baltic URSI Symposium, pp. 117-120, May 2018.

[23] O. Luukkonen, S. I. Maslovski, and S. A. Tretyakov, "A Stepwise Nicolson–Ross–Weir-based Material Parameter Extraction Method," IEEE antennas and wireless propagation letters, Vol. 10, pp. 1295–1298, Nov 2011.

[24] D.-K. Lee, J.-H. Kang, J.-S. Lee, H.-S. Kim, C. Kim, J. H. Kim, T. Lee, J.-H. Son, Q-H. Park, and M. Seo, "Highly Sensitive and Selective Sugar Detection by Terahertz Nano-Antennas," Scientific reports, Vol. 5, 15459, Oct 2015.

[25] P. Parasoglou, E. P. J. Parrott, J. A. Zeitler, J. Rasburn, H. Powell, L. F. Gladden, and M. L. Johns, "Quantitative Water Content Measurements in Food Wafers Using Terahertz Radiation," Terahertz Sci Technol, Vol 3(4), pp. 176–82, Dec 2010.